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PROMISING PROSPECTS OF NON-UNIFORM INDOOR ENVIRONMENT



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“A non-uniform indoor environment can reconcile the demand for a healthy, comfortable environment with the objective of low carbon emissions.”

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Summary

Traditionally, the indoor environmental parameters taken into account when designing and regulating air conditioning are considered to be uniform within a given area, which can result in high energy consumption and poor indoor air quality. However, a non-uniform environment allowing differentiated parameters to be maintained according to the needs of the occupants in various sectors of that zone can be decisive in achieving greater efficiency.

This Informatory Note synthesises current knowledge of technologies for creating demand-oriented non-uniform indoor environments. In particular, it provides information on the advanced air distribution schemes to be implemented, the heating/cooling loads to be taken into account, the ventilation rate required as well as the regulation of this type of environment. The areas of application of these technologies, ranging from workspaces to shopping centers, airports and data centres, are reviewed.

Finally, a series of recommendations is made to prioritise the challenges to be met to enable the development of these highly promising technologies in terms of energy savings and air quality.

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Introduction

Traditionally, the parameters of indoor environment that are used to design and regulate air conditioning are generally regarded as uniform, which leads to high energy consumption and poor indoor air quality. On the contrary, a non-uniform environment that maintains differentiated parameters at multiple locations as required would be instrumental in achieving better efficiency. Consequently, more research has shifted from mixing ventilation, oriented to uniform environments, to advanced air distributions, oriented to non-uniform environments. The design guidelines, control strategy, and energy saving effect for non-uniform air distributions have been widely investigated. Furthermore, the continuous COVID-19 epidemic has truly demonstrated the harm of virus transmission, reminding the public the importance of effective measures to reduce the exposure of personnel to the virus. More efforts need to focus on the local areas occupied by personnel so as to create a non-uniform healthy environment. This Informatory Note provides knowledge on prediction, air distribution, and regulation of non-uniform indoor environment.

Characteristics of non-uniform indoor environment

In this type of environment, the room air parameters cannot be considered as uniform, and this non-uniformity of parameters needs to be fully interpreted. Computational fluid dynamics (CFD) is an effective method for describing their distributions [1]. However, the time cost is high because of the laborious iteration process, and it is not suitable for the on-site prediction and prediction-based adjustment of air supply parameters. The fast fluid dynamics (FFD) method was then introduced to reduce the computing cost by using simple and low-order schemes [2].

The above methods mainly predict the parameter distributions for a specific scenario. It is also necessary to distinguish how the indoor parameters are explicitly affected by each influencing factor, such as the supply air from each inlet and indoor scalar source, and by their initial distribution. The indoor air velocity field is the key in transmitting contaminants and heat. In a mechanically ventilated room, the airflow is relatively stable for a period of time, and the velocity field can be assumed to be fixed. In these circumstances, some quantitative indicators can be defined to characterise the inherent properties of the flow field. Murakami [3], Kato et al. [4], and Sasamoto et al. [5] introduced a scale for ventilation efficiency (SVE), and a contribution ratio of indoor climate (CRI) index to quantify the influence of each factor on the steady concentration and temperature at an arbitrary position, through which the factor predominantly affecting the air parameters at each position can be identified.

In addition to a stable environment, there are various occasions where transient temperature, humidity or contaminant concentration need to be controlled. When the flow can be rapidly stabilised, it can be considered that scalar parameters undergo transient changes in a fixed flow field. Li and Zhao [6] used the accessibility index to reveal the time-averaged effects of influencing factors. Two indexes were proposed, namely accessibility of supply air (ASA) and accessibility of contaminant source (ACS). ASA quantifies the degree to which the supply air from each air inlet reaches various indoor locations over a period of time, while ACS quantifies the impact of each contaminant source on various indoor locations over a period of time. A linear superposition expression for the time-averaged contaminant concentration at an arbitrary position was established based on the accessibility index [7].

Ma et al. [8] further defined the transient accessibility index and established an expression for the transient contaminant concentration, as shown in Figure 1. The transient accessibility indexes of each air supply inlet, contaminant source, and initial condition of contaminant are first calculated based on the fixed flow field. Based on the indexes, the contributions of all the air supply inlets, contaminant sources, and actual initial condition of contaminant to the indoor contaminant distribution can be described separately through linear superposition. The final contaminant distribution is obtained through the superposition of the contributions of these three parts. The mentioned indexes and expressions are helpful to reveal the contribution of any influencing factor to the formation of indoor non-uniform environment. Moreover, the concise expressions can be conveniently used for the evaluation, design, and control of non-uniform environment.

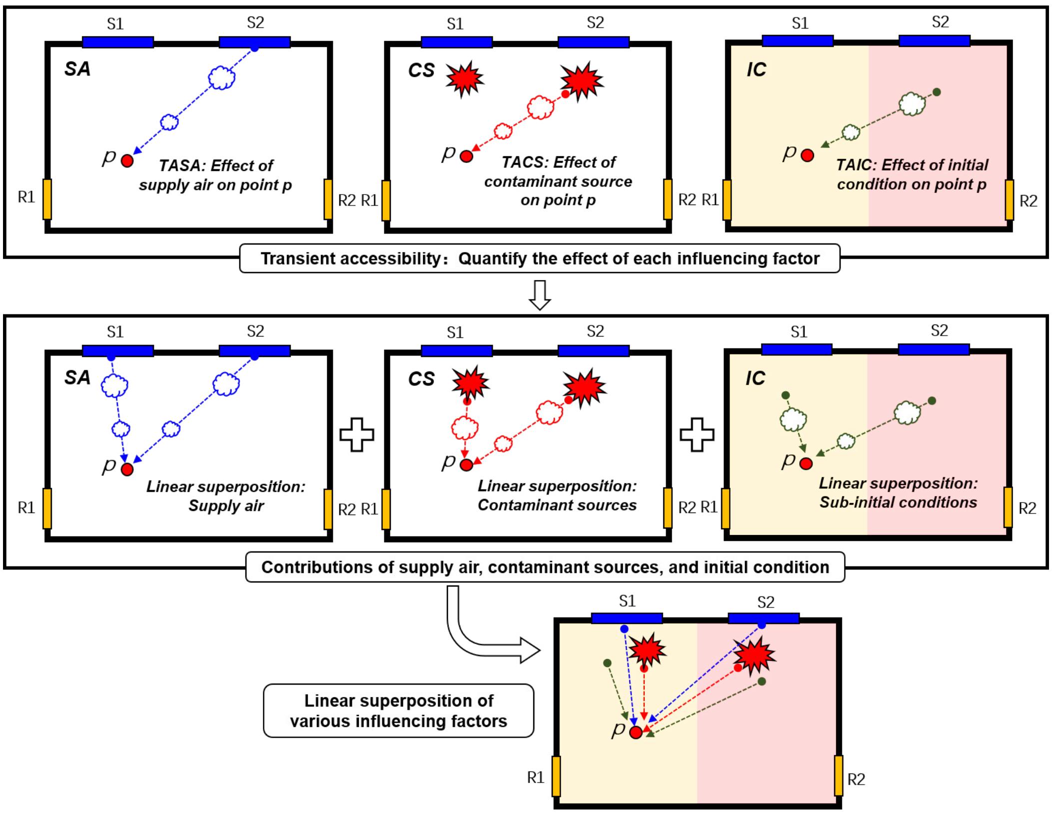


Figure 1

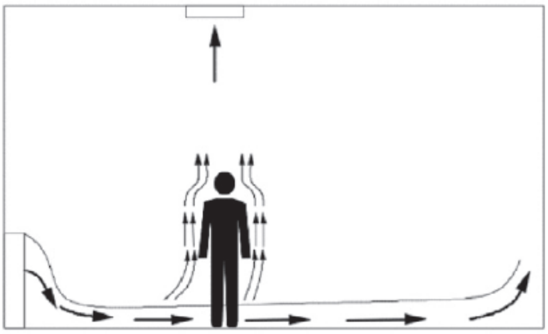
Linear superposition relationship for contaminant distribution [8]

Recently, some prediction models of the non-uniform environment have been trained based on the dataset collected from simulations or measurements. Ren and Cao [9] proposed a low-dimensional linear ventilation model-based artificial neural network to predict non-uniform contaminant concentration using limited monitoring data as input. By fitting the test data collected from the actual ventilated room, Zhang et al. [10] established a relationship between the predicted mean vote (PMV) at each subzone and the air supply and exhaust parameters to satisfy the differentiated thermal preferences in multiple subzones. The various prediction relationships are the basis for the creation of non-uniform environment, and are of great significance for knowledge, design, and control of such environment.

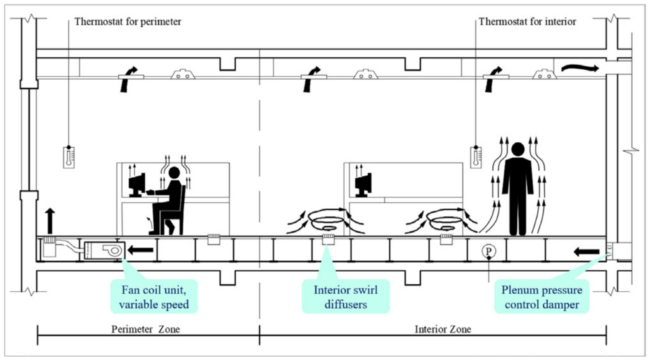
Advanced air distributions of non-uniform indoor environment

Different air distribution patterns are implemented depending on the variation of occupancy demand. Mixing ventilation (MV) is designed in relation to the overall environment maintenance of the room. When shifting the target to the working area, the processed air is not mixed with indoor air but is delivered to the working area for direct and efficient air exchange, and removal of heat and contaminant. Therefore, less energy consumption and higher ventilation efficiency can be achieved. A series of advanced air distribution patterns have been put to the fore, such as displacement ventilation (DV) [11], underfloor air distribution (UFAD) [12], and impinging jet ventilation (IJV) [13], as illustrated in Figure 2 [14]. To respond to the thermal discomfort under elevated indoor temperature for energy saving, Lin et al. [15] proposed delivering the processed air to the head level through stratum ventilation (SV): the air flow in the working area is strengthened, which offsets the thermal sensation caused by temperature elevation. Li et al. [16] suggested wall attachment ventilation (WAV). With this method, the air supply jet is delivered downwards along the wall, impinges on and spreads over the floor, generating an air layer in the occupied zone. The terminal of WAV is arranged in the upper space, saving the occupied space, and in the meantime, WAV achieves temperature and velocity fields similar to DV. With the demand for a healthy environment, Cao et al. [17] proposed the protected occupied zone ventilation (POV) system to separate an indoor environment into several subzones by using low turbulent plane jets. POV can destroy the high-concentration exhalation flow directed into the protected subzone.

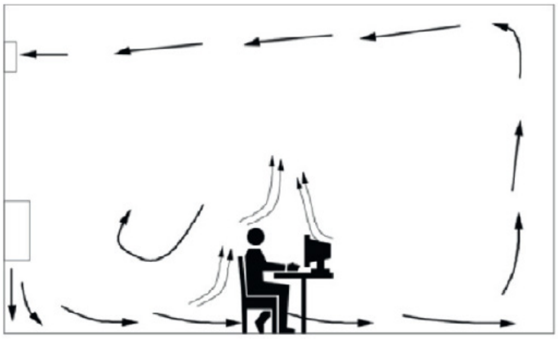
The existing air distribution patterns are in a single mode, which cannot always perform efficiently in response to the changeable personnel occupation and indoor source distribution scenarios. To handle changing indoor demand scenarios, Shao et al. [18] proposed multi-mode ventilation (MMV). For this technique, a certain number of typical occupancy and indoor source scenarios are first selected, and several efficient airflow modes are designed to respond to them. The airflow mode candidates are optimised and integrated into a MMV system. During operation, the airflow mode that can efficiently meet the real-time demand is determined and then switched through air-valve adjustment. The schematic of MMV is shown in Figure 3, where two scenarios are demonstrated. In reality there may be more than two scenarios, in which more airflow modes can be determined for the integration and switching of the MMV system.



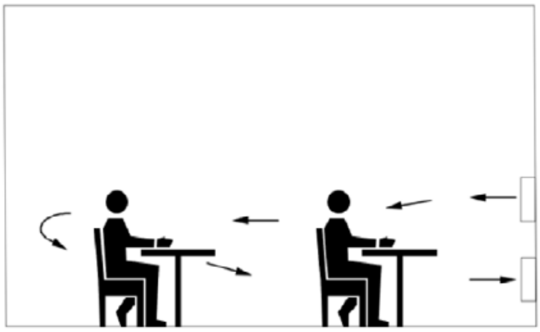
(a) Displacement ventilation



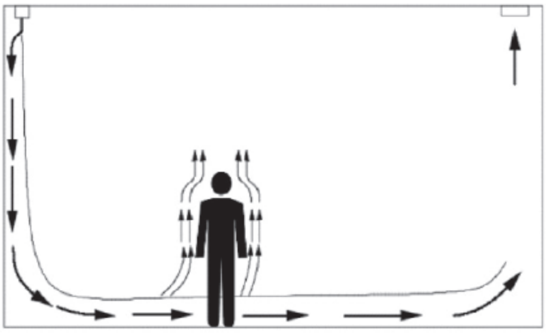
(b) Underfloor air distribution



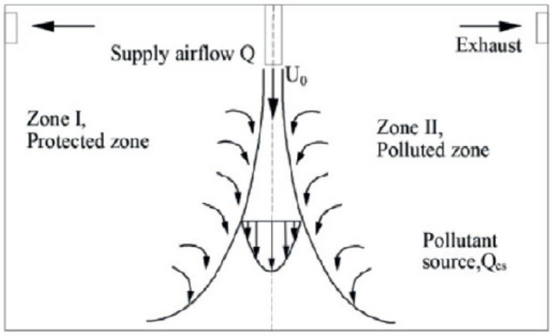
(c) Impinging jet ventilation



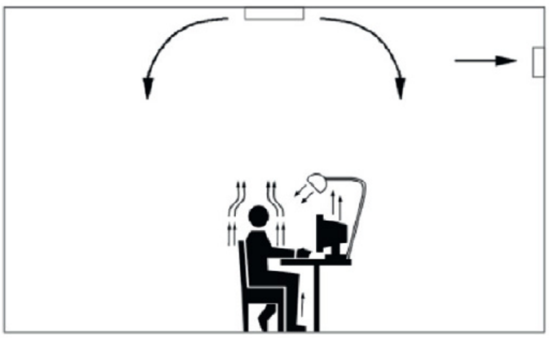
(d) Stratum ventilation



(e) Wall attachement ventilation



(f) Protected occupied zone ventilation



(g) Personalised ventilation

Figure 2

Schematics of advanced air distribution patterns [14]

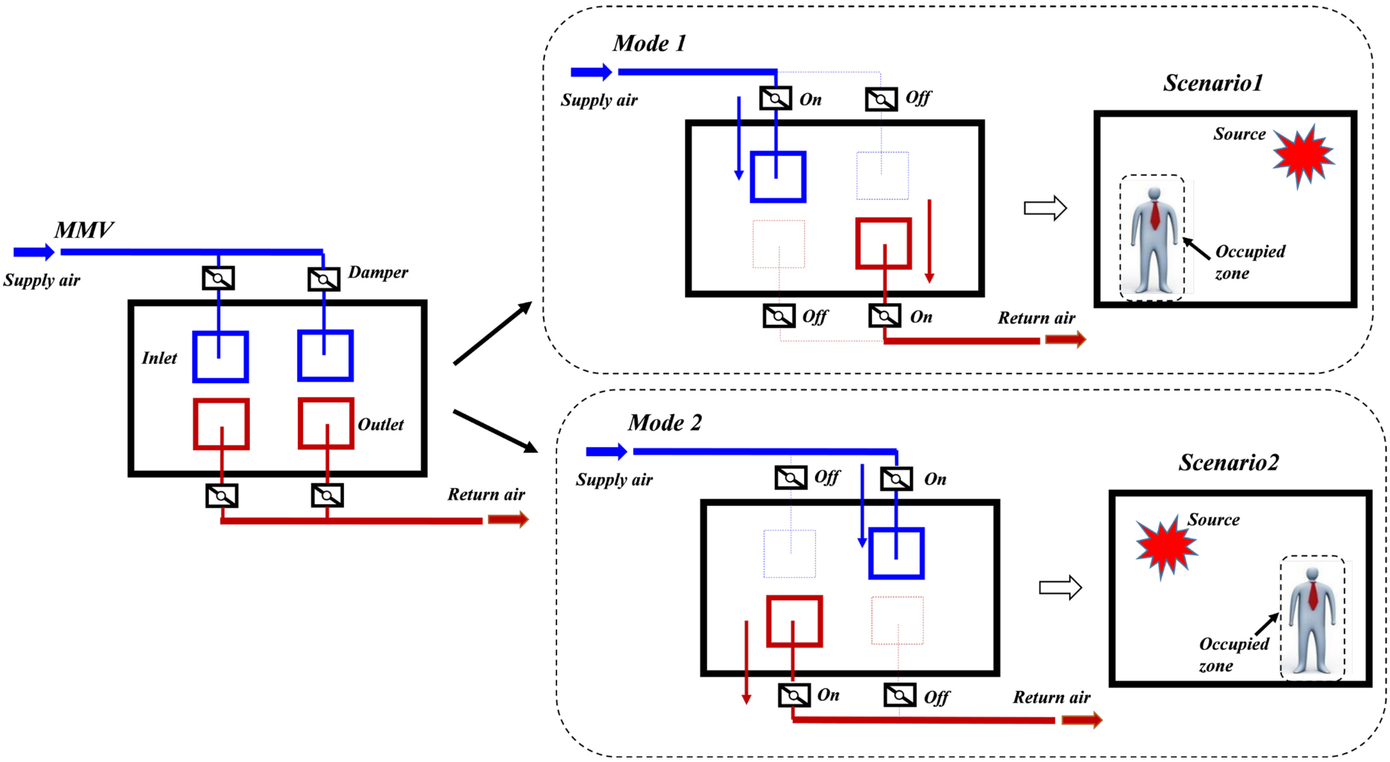


Figure 3

Schematic of MMV [18]

Most of the above advanced air distribution patterns focus on maintaining the average regional environment and do not consider the individual requirements of occupants in different locations. Personalised ventilation (PV) is a good solution [19]. The personalised air supply terminal is arranged in the workstation area, and processed fresh air is directly supplied to the breathing zone of the personnel to improve air exchange and pollution removal performance. Meanwhile, the personnel have independent control over the air parameters in their respective areas. An additional background air conditioning system is required for PV. Recent studies have investigated the use of collective air distributions to maintain a personalised environment in multiple subzones. For instance, Zhang et al. [10] took advantage of certain non-uniform characteristics of SV and improved the satisfaction of the desired thermal environment in multiple subzones through the synchronous optimisation and adjustment of the air supply parameters from multiple inlets. Shao et al. [20] further revealed that greater personalised environment potential can be achieved between subzones through the independent adjustment of the air supply parameters from different inlets. The shift in ventilation target has brought about remarkable changes in air distribution patterns.

Cooling/heating load of non-uniform indoor environment

Creating a non-uniform environment is more complex that creating a uniform environment. When ensuring the same temperature and humidity in a region, supply air parameters may be different, which means that the cooling/heating load also differs. To more clearly describe the cooling/heating load in a non-uniform environment, the local cooling load (LCL), Q_{local}, was introduced, as described by Eq. (1) [21]:

$$Q_{local} = \sum_{j=1}^{N_C} q_j \bar{A}_{j,local}$$

Equation 1, where q_j is the intensity of the j^{th} heat source, W; $\bar{A}_{j,local}$ is the accessibility of the j^{th} heat source to the target zone; N_C is the number of heat sources.

According to Eq. (1), the LCL is related not only to the intensity of heat sources, but also to the accessibility of heat sources. Obviously, the LCL is not equal to the traditional cooling load, which is the sum of the intensities of all heat sources. Advanced air distribution can reduce the accessibility of the heat source and the LCL can be significantly less than the traditional room load. Conversely, poor air distribution would lead to a higher LCL, as shown in Figure 4 [22]. Besides, the location and size of the target zone, as well as the layout of heat sources, influence the LCL.

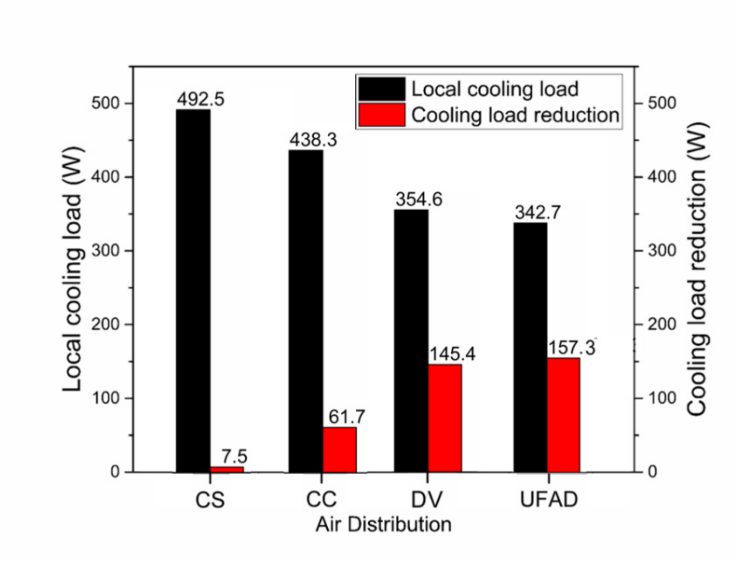


Figure 4

LCL of different air distributions in a room (CS–ceiling supply and sidewall return, and CC–ceiling supply and ceiling return) [22]

The system cooling load (SCL) of the air conditioning system is more important than the LCL because it is directly related to energy consumption. Liang et al. [23] divided the SCL into three parts, fresh air cooling load, LCL and return air cooling load. As shown in Figure 5, the LCL can be reduced by creating advanced air distribution, but the return air temperature will be higher than indoor set temperature to increase the return air cooling load. Therefore, the SCL of the air conditioning system in the non-uniform environment may not be significantly reduced compared to that in the uniform environment. However, due to the decoupling of the return air, fresh air, and indoor cooling load, it is possible to use low-grade cold sources (e.g. cooling water generated by a cooling tower) to process return air and fresh air, thereby achieving significant energy savings [23].

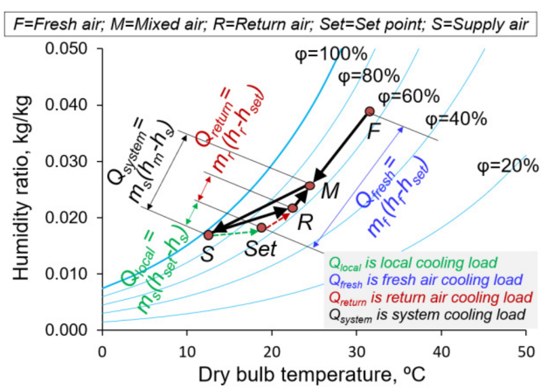


Figure 5

SCL of primary return-air conditioning system [23]

Required ventilation rate of non-uniform indoor environment

In a non-uniform environment, the layout of indoor sources has a significant impact on the target zone. The required ventilation rate may be significantly different from that in a uniform environment. For a non-uniform environment, the influence of contaminants on the target zone can be characterised by the accessibility of the contaminant source ($\bar{A}$). Liang and Li [24] introduced the required ventilation rate, Q, to satisfy the contaminant concentration requirement in the local zone. Q is defined by Eq. (2):

$$Q = \frac{J\bar{A}}{C_{set} - C_S}$$

Equation 2, where J is the emission rate of the contaminant source, kg/s; C_{set} and C_S are the settings of contaminant concentration and air supply concentration, respectively, kg/m³.

For the traditional uniform environment, reducing the emission rate of the contaminant source is seen as the only way to decrease the ventilation rate. However, from a non-uniform perspective, another effective way to do so is to reduce the accessibility of contaminant source. In an ordinary ventilated room, accessibility can be significantly changed by creating different air distribution patterns, thereby decreasing the required air volume. According to a case study, the required ventilation rate can be 21.3% lower than the nominal ventilation rate with advanced air distribution, while the former is significantly higher than the latter with poor air distribution [24], as shown in Figure 6.

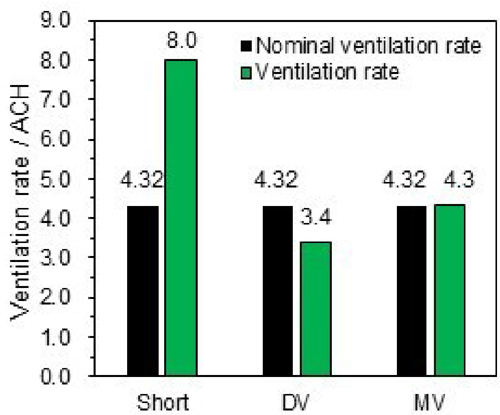


Figure 6

Influence of air distribution on the ventilation rate [24].

For a ventilated space with multiple air supply inlets, efficient air distribution can be achieved by setting the air supply volume of each inlet to different values so as to reduce the accessibility of contaminant source. The method is applied in semiconductor fabs [25]. The entire space is large, but there are generally few personnel, and personnel represent the main particle sources. By increasing the local air supply volume above the personnel, the particles they emit can be quickly discharged from the lower space. Meanwhile, the air supply volume above other large areas can be greatly decreased, thereby significantly reducing the overall air supply volume of the entire semiconductor fab. In a specific case, the resulting clean air volume was reduced by 67.3%.

Regulation of non-uniform indoor environment

In addition to the design of air distribution patterns, the adjustment of non-uniform environmental parameters is critical. Although their actual application remains limited, some relevant scenarios for the control of a non-uniform environment have been studied. In a non-uniform environment, the real-time locations of indoor sources need to be identified, as well as those of the target object, i.e. the personnel. Depending on the dynamic indoor sources and personnel scenarios, air supply parameters need to be optimised and adjusted. A variety of methods to identify the locations and intensities of pollution sources are proposed. Zhang and Chen [26] and Zhang et al. [27] developed a contaminant source identification method using inverse CFD modelling. The source location can be identified theoretically. Shao et al. [28] also established a sensor-based source identification method: number, locations and release rates of the sources were identified in an actual chamber.

With occupancy positioning and activity information, improvements of regular HVAC systems can be achieved from many aspects. Operationally, HVAC systems can avoid serving vacant areas [29] or systematically adopting the design load in working zones [30], which helps realise large energy conservation. Occupant counting and location has been studied and achieved using various methods. For instance, temperature and CO_2 sensors are extensively installed in HVAC control systems [31];

by detecting the infrared energy from occupants, passive infrared (PIR) sensors can offer a huge field of view (FOV) and distance. Based on radio frequency signals, radio frequency identification (RFID) systems can detect and localise occupants using specific tags [32]. In recent years, Bluetooth low energy (BLE) and Wi-Fi technologies have been widely used and can provide indoor positioning information in large spaces [33, 34]. With the rapid development of machine vision, a series of camera-based occupancy detection and positioning systems have also been studied [35]. The convolution network method was employed to analyse and classify head windows with 94.3% accuracy [36]. Multiple cameras allocated at the entrances and inside the rooms have been employed to address the problem of intrusiveness, using a dynamic Bayesian network [37]. At the same time, many 2D image-based human pose estimation (HPE) algorithms have been developed. These HPE algorithms made capturing and extracting the skeleton key points from 2D images much more feasible than before for a multitude of applications. A previous study [38] proposed an occupancy positioning system with multiple conventional surveillance cameras capturing 2D images from different angles (Figure 7).

(a) Camera 1 *(b) Camera 2* *(c) Camera 3* *(d) Camera 4* *(e) Results of positioning*

Figure 7

Skeleton key point extraction results and positioning results [38]

Traditional ventilation systems struggle to effectively measure and evaluate the non-uniform distribution in indoor environment, making it difficult to meet the dynamic demand of non-uniform environment. With the development of sensors and microelectronic technology, various information has been involved in the control system. CO_2 sensors first provided input to rapidly predict indoor contaminant concentrations. Then, the predictions of the concentration field have been further used in the ventilation assessment of the control system to achieve the optimal ACH [39]. Combined with historical meteorological data, a control strategy capable of modelling and detecting dynamic patterns of CO_2 level is utilised to modulate the ventilation rate in real time. With occupancy position information a multi-terminal HVAC system can save a lot of energy by serving only the occupied region of the room [38]. The relationship between air supply and exit parameters, as well as air parameters at indoor locations can be obtained and used to accurately predict the non-uniform distributions of the indoor air temperature and velocity. With this method [40], non-uniform thermal environment can finally be modelled and controlled for thermal comfort and energy efficiency. Based on the linear superposition relationship under the fixed flow field, an optimisation model for air supply parameters was proposed to satisfy the personalised requirements at multiple locations [41]. Some achievements have been made regarding the control of non-uniform environment, but the related work is still in its initial stage and needs to be pursued.

Applications of non-uniform environment technology

A certain number of practices have been related to non-uniform environments. As a typical scheme for working area ventilation, DV has been applied in many contexts, such as meeting rooms, classrooms, airports, shopping centres, etc. [14] UFAD has been used in commercial buildings that require high layout flexibility, and widely used in data centres in recent years to remove a large amount of heat. IJV performs well when applied in offices, classrooms, and industrial buildings [42]. In general, maintenance of a non-uniform environment for the working area has been widely recognised as critical and implemented. As a superior air distribution pattern, PV has been applied in offices, auditoriums, etc. With the increasing attention to a healthy environment, especially since the COVID-19 epidemic, research on healthy ventilation in confined spaces has been strengthened. PV, SV, and air distributions based on air curtain barriers (such as POV) have shown good performance in inhibiting the cross infection of respiratory viruses [43-45] and are expected to be applied in buildings such as hospitals. In the future, the system design of non-uniform environment is expected to be more efficient in dealing with changing and personalised demand scenarios. The maintenance of non-uniform indoor environment is human-centred, therefore, real-time acquisition of personnel occupation information is the key to air parameter adjustment. To that end, information technologies such as infrared, RFID, Bluetooth, Wi-Fi, and machine vision have been applied in the ventilation and air conditioning field, and the targeted ventilation and adjustment can be carried out through the real-time determination of the number and location of personnel. It is expected that there will be more developments and applications of intelligent ventilation technology towards a future intelligent non-uniform environment.

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IIR recommendations

A non-uniform indoor environment can reconcile the demand for a healthy, comfortable environment with the objective of low carbon emissions.Up to now, studies have focused on the characteristics of the non-uniform environment. A variety of source identification and personnel positioning methods have gradually been applied in actual engineering. However, there remain challenges regarding the design and regulation of the non-uniform environment. Economic analysis should be implemented for the proposed technology. Further work should be carried out and further applications implemented worldwide. The recommendations are as follows.

- The existing air conditioning and ventilation system is designed for a single working condition (normally, the extreme condition); however, multiple typical working conditions exist with the variation of indoor sources and personnel distribution. The system design should efficiently handle various typical scenarios, rather than just one design condition.

- The target should shift from the satisfaction of the entire room space to the satisfaction of the occupied space. The actual occupied space is generally only part of the total space. The personalised preferences from occupants in multiple subzones should be met to achieve a more satisfactory environment.

- At present, air supply terminals with fixed positions are usually used, and the adjustment ability of the air volume and of the supply air direction is very limited. More efficient terminals adaptable to various scenarios should be developed for engineering in the future.

- The regulation of a non-uniform environment is more complicated than that of a traditional uniform environment. In practical applications, there may be different parameter requirements among target zones, and the position of the target zone may change. More research is needed into how variations of supply air velocity, temperature and direction affect different subzones (cross effect). Modern, intelligent sensing technology needs to be integrated into the prediction of indoor environment, and more reliable intelligent regulation methods for non-uniform environment need to be developed under real-time detection.

- More efforts should be made to raise awareness of the benefits of non-uniform environment among the decision-makers and the public. Technical personnel in the field need to be trained to master the design concept and related technology of non-uniform environment. Standards and specifications for non-uniform environment need to be formulated to guide its design.

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